CAN WE GO CIRCULAR ?

On the multifaceted challenges of facilitating shredder fines valorisation in the Swedish context

Tharaka Gunaratne

Linköping Studies in Science and Technology

Licentiate Thesis No. 1864

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Licentiate Thesis No. 1864

ISBN: 978-91-7929-932-3

ISSN: 0280-7971

Printed by:

LiU-Tryck, Linköping 2020

Distributed by:

Linköping University

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SE-581 83 Linköping, Sweden

Abstract

In concomitance with the growing developments around the circular economy concept in the region, the resource recovery and recycling of industrial production residues is increasingly being envisaged in the European Union and its member states. The role of the recycling industry has become ever important in this context. The shredding industry is based on shredding discarded products such as end-of-life vehicles, and municipal white goods, and subsequent retrieval of (primarily) metals. Shredder fines (or fines) is a heterogeneous fine-granular production residue of this industry, which is currently disposed of. Shredder fines presents, and will continue to do so in the foreseeable future, several challenges that need to be addressed. It creates a disposal problem given the shrinking landfill availability and incurs handling costs to the shredding industry. Furthermore, it reduces our resources efficiency in general.

This thesis aims to contribute knowledge on the challenges of facilitating the valorisation of shredder fines in the context of Sweden. In doing so, the current situation concerning fines and its management was investigated by addressing the research questions; 1) What is the resource potential of fines generated at the studied shredding plant, and 2) Why is the current disposal-oriented management of shredder fines sustained in Sweden. There, a systems perspective was employed, where the research questions were addressed on the material, actor, and institution levels, based on three scientific articles, which are appended.

The studied material carries a certain amount of potentially recoverable resources, nevertheless shows a significant need for upgrading pertaining to the user requirements and regulatory standards of different recovery applications. The full recovery of fines requires integrated processes that could simultaneously harness these resource opportunities and resolve the material constraints. When it comes to the current practice of managing fines in Sweden, the utilisation in landfill covering offers the shredding companies a secure outlet for the material, given it is a well-established practice that has evolved over decades of operations and there is still a significant demand for landfill cover materials. Additionally, it provides shredding companies with a legislatively-compliant low-cost disposal option for managing fines. On the other hand, the complex materiality, lack of marketability of secondary raw materials (SRMs), and unfavourable governmental regulation of waste recovery create strategic disincentives for shredding companies in opting for fines valorisation.

Fines valorisation calls for change in the well-established current practice of utilising the material in landfill covering. Thus, drastic policy measures such as phasing out landfilling and mandating resource recovery and recycling of fines are required to remove the incentives for fines disposal and compel the shredding industry to seek valorisation alternatives for its management. In order to ensure long-term sustenance, applications based on fines valorisation need favourable and more predictable circumstances and settings on different societal levels. There, secure outlets for

potential fines-derived SRMs is one of the essential elements. Governmental interventions to create demand and alleviate valorisation investments via market and financial instruments play a significant role in that regard. The other primary requirement to facilitate fines valorisation in the long term is to set clear market and regulatory playing rules. Established supply and demand structures would enable clear pricing mechanisms for fines-derived SRMs and accurate economic assessments of fines valorisation, thus reducing the investment risk for shredding companies. On the other hand, clear regulatory standards and favourable regulatory practices would reduce the uncertainty of the realisation of valorisation applications and gain trust among actors.

Acknowledgement

Sincere appreciation goes to my main supervisor Joakim Krook, for the guidance and support in doing the research as well as writing the articles and this thesis. I would also like to acknowledge the guidance and support from my co-supervisor Hans Andersson in writing the articles and this thesis.

Special thanks go to the Mistra Closing the Loop II program for funding this research, and Hitomi Lorentsson at Stena Recycling AB for facilitating the field work and empirical data collection.

I would also extend my gratitude to all the colleagues at the Environmental Technology and Management division of Linköping University, for the pleasant work environment.

Finally, I would like to thank my mother for the efforts in making me who I am, and my wife for sharing these years in life with me.

List of appended articles

The author of this thesis has been the first author of all the three appended articles.

Article I: Published

Gunaratne, T., Krook, J., Andersson, H., Eklund, M., 2019. Guiding future research on the valorisation of shredder fine residues: A review of four decades of research. *Detritus*. Vol 09. pp 150-164.

Contribution:

The first author performed the selection of previous literature, the review and the analysis. The first author has also primarily written the text.

Article II: Published

Gunaratne, T., Krook, J., Andersson, H., Eklund, M., 2019. Potential valorisation of shredder fines. Towards integrated processes for material upgrading and resource recovery. *Resource, Conservation, & Recycling*. Vol 154 (2020) 104590.

Contribution:

The first author performed the field work, that is, sampling and the preparation of the material for characterisation, the data collection, and the analysis. The first author has also primarily written the text.

Article III: Draft

Gunaratne, T., Krook, J., Andersson, H., Current practice of managing the waste of waste. Policy, market, and organisational factors influencing shredder fines management in the Swedish context.

Contribution:

The first author conducted the interviews that provide the core empirical data for the writing of the article, processed and analysed the data. The first author has also written the draft.

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1 Introduction

This chapter presents the wider socio-technical context of and motives for the research, followed by a description of the aim and research questions. It ends with an outline of the following chapters of the thesis.

Circular economy, which could be considered a strategy to restore the environmental and economic balance of industrial activity (Ghisellini et al., 2016), is increasingly envisaged in today's societies. There, in contrast to the traditional linear economic model of production and consumption, closing the material loops is of prime significance. However at present, our handling of materials typically involve considerable losses along their entire life cycles, both in terms of matter and resource quality (Material Economics, 2018). At the end of product life, current collection and recycling processes are capable of retaining the value of only a fraction of the materials contained in the waste streams, while the main amounts are either down cycled to low-quality resources or disposed of (Baccini and Brunner, 2012). Many recycling processes focus on only one or a few targeted outputs despite many incoming materials, and hence, result in generating large quantities of heterogeneous residues. Such residues, i.e. the *waste of the waste*, are often technically challenging and economically unappealing to recover (Fischer, 2006), hence disposed of into landfills in many parts of the world (Lam et al., 2010; Vermeulen et al., 2011). This practice causes a continuous loss of resources and adds waste disposal costs to the recycling industry.

Since the mid-20th century, the shredding of complex end-of-life products to recover some targeted valuable resources has gradually evolved, and nowadays this practice plays an important role in the recycling industry in several parts of the world. In this industry, waste streams such as end-of-life vehicles (ELVs), municipal white goods, and industrial metallic scrap are shredded (Santini et al., 2012; Vermeulen et al., 2011), primarily for the subsequent recovery of metals such as iron, aluminium, and copper. Upon the initial separation of these metals, a heterogeneous outflow consisting of a mixture of the non-recovered materials (e.g. metals, plastics, textile and fibre, rubber, foam, glass, wood and gravel) is generated (Cossu et al., 2014; Vermeulen et al., 2011). This material, called the shredder residue, is often landfilled around the world (Cossu and Lai, 2015; Vermeulen et al., 2011). In certain countries, e.g. in Sweden and Belgium, advanced processing is used for further recovery of materials such as metals and plastics from the larger size fractions of this residue. Nevertheless, the fine-granular fraction of the shredder residue, which is called *shredder fines* or merely *fines*, is virtually always disposed of (Allen and Fisher, 2007; Santini et al., 2012).

Shredder fines, like other heterogeneous residues, are typically regarded as low-quality materials due to that they constitute a blend of potentially valuable, inert, and hazardous components (Ahmed et al., 2014; Fiore et al., 2012; Morselli et al., 2010). Without further processing, this material offers limited utility. The materiality of fines can significantly vary between different shredding plants due to differences in the feed material, shredding units, and post-shredder resource recovery processes. In previous

literature, fines have been commonly recognised as the 0-20 mm fraction of the shredder residue (Vermeulen et al., 2011). The share of fines could comprise 10-30 % of the material input to the shredder, and 25-70% of the shredder residue (Cossu et al., 2014; Cossu and Lai, 2015). Globally, about four million tonnes of fines are annually generated from the shredding of ELVs alone (calculated from Fiore et al. (2012), and Vermeulen et al. (2011)). The total amount of fines generated is expected to be a couple of times more than that because most shredding plants typically shred a mix of waste streams.

In Sweden, the advancement in post-shredder treatment processes have gradually enabled the shredding industry to recover materials from the smaller fractions of shredder residue overtime. Consequently, in some plants, the particle size of fines has been reduced from 20 mm to less than 10 mm during the last two decades. At present, fines is primarily utilised as landfill cover material in the country, whereas in certain occasions it is also landfilled. On the one hand, such utilisation in landfill covering incurs the loss of valuable resources e.g. metals, energy carriers, minerals, etc. and disposal costs to the shredding companies. On the other hand, the landfills are gradually phasing out in the country (Swedish EPA, 2010a) and the EU is imposing stringent recovery and recycling¹ targets for end-of-life vehicles (European Commission, 2000). Hence, this disposal-oriented practice of fines management is unlikely to be an option in the long run. Several other countries in the region such as Netherlands, Denmark, Belgium, and Finland, which are socio-economically comparable to Sweden, have already drastically reduced the disposal of such heterogeneous residues via waste-reutilisation policies and practices (Johansson, 2018). Thus, in order to improve resource efficiency, reduce costs, and avoid future disposal problems, the Swedish shredding industry should seek alternative management options based on value addition (via upgrading and resource recovery) - also referred to as valorisation (Martin, 2013; Pontikes and Malfliet, 2016) - of fines. Additionally, in order to address these objectives, valorisation should target the full recovery of fines, that is, both the recycling of specific valuable resources and the bulk utilisation as substitute raw material.

At present, very little is happening in practice when it comes to improving fines management, and the research on fines valorisation is still in an early phase. The potential valorisation of fines can be influenced by factors related to multiple aspects on different levels, hence, its development and implementation requires multi-faceted knowledge. Previous research concerning other heterogeneous residues such as shredder residues and municipal waste incinerator bottom ash (municipal bottom ash), show various such aspects on the material, institution, and actor levels. Material-level aspects such as, the chemical and physical composition (Ahmed et al., 2014; Dou et al., 2017) are necessary to establish in order assess the occurrence of potentially recoverable

¹ "Recovery" is any operation by means of which a waste is used or being prepared to serve a particular function by replacing other materials. "Recycling" means any recovery operation by which waste materials are reprocessed into products, materials, or substances whether for the original or other purposes. (European Commission, 2008).

resources and potential material contaminants. Such knowledge enables the identification of potential users of various fines-derived resources and the need for process development to generate such resources. The institution-level aspects are primarily two fold. Formal-institutional aspects (governmental aspects) such as administrative instruments (Nayak and Apelian, 2014) and local-authority regulation (Johansson, 2018) would provide the overall governance of applications based on fines valorisation, while market instruments (Dubois et al., 2015) could be used to provide external stimulation for such applications. Markets for secondary raw materials (SRM) are informal institutions. There, aspects such as demand for SRMs primarily determine the economic prospects (Johansson et al., 2017) of valorisation-based recovery applications (valorisation applications) for fines. The actor-level aspects such the waste producers' capacities to influence material flows (van Beers et al., 2009), and how they have internally organised for it, determine the actual practice of managing fines.

A systemic knowledge on how these various aspects influence the current practice of fines management is lacking. The realisation of fines valorisation strategies would involve institutional conditions and responsive actors, in conducive to driving fines away from disposal, and towards investing in knowledge and technology development for resource recovery. Enabling such circumstances and settings naturally requires knowledge that can explain the prevailing practice of managing the residue (Nitivattananon and Borongan, 2007; Obernberger and Supancic, 2009). A systems perspective here of facilitates viewing the current practice of managing waste as a consequence of various factors on different levels acting together influencing each other (Andersson et al., 2019b; Iacovidou et al., 2017). The lack of such knowledge renders the identification of necessary measures and setting priorities for the development and implementation of valorisation applications largely difficult.

The development of valorisation applications requires technical knowledge, which also constitutes the main focus of virtually all fines-related research. However, there is a lack of a holistic approach in such studies. For instance, the material characterisation studies are often confined to assessments of one or a few out of many chemical and physical properties, which are performed based on one or few randomly collected samples and involving particular size fractions of the material, thus overlooking variation (Edo et al., 2013; Fiore et al., 2012; Morselli et al., 2010). Consequently, our knowledge on the resource potential of fines, even at the plant level, is largely limited. This lack of comprehensive knowledge on the resource potential, is in turn reflected in the narrowly-conceived approaches of the process development studies concerning fines recovery. Generally, these studies are confined to either the retrieval of one or few specific resources (Gent et al., 2015; Lewis et al., 2011; Santini et al., 2012) or the bulk utilisation of fines as a substitute material, e.g. in ground construction (Péra et al., 2004; Rossetti et al., 2006). A large share of the material is left for disposal in the case of former, whereas the opportunity to recycle valuable resources is lost in the latter. Consequently, the full recovery of fines is overlooked. Additionally, these studies largely confined to lab-scale processes, in which, the effects of input-composition variations and market requirements on outputs are disregarded. Thus, the applicability of the developed processes in handling the material and delivering marketable SRMs is yet to be proven.

These inadequacies in knowledge concerning fines and its management need to be addressed in order to identify the challenges and measures for facilitating change and eventual development and implementation of fines valorisation. The valorisation of *waste-of-the-waste* plays a crucial role, not only in reducing the disposal costs and avoiding future disposal problems of the recycling industry, but also in increasing our resource efficiency via closing the material loops, which is the foundation of circular economy.

1.1 Aim and research questions

The overall aim of this thesis is to contribute knowledge to facilitate the valorisation of shredder fines in the Swedish context. In doing so, the current situation concerning fines and its management is investigated in order to identify challenges that need to be addressed to enable the development and implementation of valorisation strategies. More specifically, the resource potential of fines is assessed, and the underlying factors of the current practices of fines management are analysed, via employing a systems perspective that accounts for different aspects on the material, actor, and institution levels. The resource potential is strongly linked to the materiality of fines, which is highly plant specific owing to the input materials and the employed shredding and post-shredder resource recovery processes. Therefore, a particular shredding plant located in Sweden was involved to enable systematic and in-depth characterisation of fines. The current management of fines is strongly linked to how shredding companies interpret and react to various aspects on the different levels. Therefore, a particular shredding company located in Sweden was involved in order to gain detailed insights on such factors. Subsequently, the following research questions (RQs) have been formulated.

RQ 1: What is the resource potential of fines generated at the studied shredding plant?

The addressing of this RQ intends to establish knowledge on the potentially recoverable resources in shredder fines and the material constraints that need to be addressed in order to enable recovery. Thus, fines from a specific shredding plant is strategically sampled and characterised in terms of the distribution and variation of a range of chemical and physical properties (material level). Different types of potential recovery applications are selected based on the occurrence of potential resources in the characterised material. The established material characteristics are subsequently benchmarked against the gate requirements (actor level) and regulatory requirements (institutional level) of the selected applications. Thereby, specifications are provided on the need for upgrading (resolving material constraints), and the potentially recoverable quantities of fines in each application. Such knowledge provides the basis for guiding process development for valorisation, and eventually, the full recovery of the material. The assessed resource potential is specific to fines produced in the particular shredding plant; nevertheless, the approach itself that is used for the resource potential assessment is generally applicable.

RQ 2: Why is the current disposal-oriented management of shredder fines sustained in Sweden?

The addressing of this RQ intends to establish the underlying factors of the current practices of fines management in Sweden. That is, the incentives for shredding companies for the disposal-oriented management of fines and the disincentives for valorisation-based alternatives. This is primarily done by performing semi-structured interviews with employees of a particular Swedish shredding company, representing different functional areas connected to fines management. Thereby, the company perspective on the influence of governmental policy and regulation, and markets for SRMs (institution level), and internal organisational aspects (actor level) on the current management of fines was identified. The shredding company perspective is focused as they are considered the most central actor in the issue of fines management. The influence of the complex materiality of fines (material level) on the shredding company in managing fines is also addressed in relation to the findings from the material characterisation. The study itself is confined to a single company; therefore, the actor-level factors are plausibly specific to the company in question. Nevertheless, the insights drawn on the institution- and material-level factors are assumed to be more generalisable to the Swedish context.

The findings from addressing the research questions are finally synthesised in order to elicit the challenges of facilitating fines valorisation. Possible measures to address them are discussed in relation to challenging the current disposal-oriented practice of fines management and enabling favourable and more predictable conditions for fines valorisation. The discussion is primarily facilitated by relating to previous research on similar industrial residues.

1.2 Thesis outline

The following is a brief description of the role and the content of the subsequent chapters of the thesis.

Chapter 2: Background

This chapter presents the research-context description in relation to the state-of-the-art on the policy and practice concerning the management of heterogeneous residues, and the significance of fines valorisation in the context of circular economy.

Chapter 3: Analytical approach

This chapter presents the employed systems perspective and its different levels that characterise the analytical approach of the research. The key concepts and terms employed are framed by referring to the broader framework of related literature.

Chapter 4: Research process and method

In this chapter, first, the research journey so far, and extended abstracts of the scientific articles produced in that journey, are presented. Finally, the method used in the compilation of the thesis, and the use of the articles to address the research questions are presented.

Chapter 5: Resource potential of shredder fines

This chapter presents the findings from the first research question. The resource potential is assessed in terms of an initial feasibility assessment of fines recovery in selected applications, by benchmarking the material characteristics against the respective user requirements and regulatory standards.

Chapter 6: Factors underlying the current practice of fines management

This chapter presents the findings from the second research question. The influences of the institution-, actor-, and material-level factors in creating motives for shredding companies to sustain the current practice of fines management are established.

Chapter 7: Challenges of facilitating fines valorisation

This chapter presents a synthesis of the challenges of facilitating fines valorisation, elicited from the findings from the research questions. Possible means to address the challenges are discussed in relation to challenging the current disposal-oriented practice of fines management, and enabling favourable conditions for fines valorisation.

Chapter 8: Thesis contributions

This chapter presents the significance of this thesis's contributions in facilitating the valorisation of fines in particular as well as heterogeneous residues in general, followed by a general reflection on the circular economy concept.

Chapter 9: Conclusions

This chapter presents the major takeaway points concerning the current situation regarding fines and its management and the challenges of facilitating fines valorisation in the Swedish context.

2 Background

This chapter presents the research-context description in relation to the state-of-the-art on managing heterogeneous residues, and circular economy.

2.1 Current policy and practice concerning heterogeneous residues

In its quest for increased resource efficiency, the EU has come up with ambitious waste-management and resource policies in the last couple of decades. Since early 2000, the region has announced a long term vision of becoming a recycling society (European Commission, 2005). Recently an action plan for circular economy was published urging an increase in closing material loops via value-added recovery and recycling (European Commission, 2015). In this context, the management of heterogeneous production residues poses a challenge. The material complexity makes the recovery and recycling of such residues difficult both technologically and economically (Fischer, 2006; Vermeulen et al., 2011). Additionally, given differences in policy and market-related circumstances, the actual practice of handling such residues differ significantly among different countries (Blasenbauer et al., 2020). Sweden, in conjunction with the EU landfill directive (European Commission, 1999), has drafted several legislations to discourage the disposal of potentially recoverable residues/wastes in the beginning of this century. For instance, landfilling is subjected to a tax of 500 SEK/tonne (Sveriges Riksdag, 1999) and prohibited if the material contains more than 10% organic matter (Sveriges Riksdag, 2001). However, after two decades, the management of heterogeneous residues is still not practiced outside of landfills. Waste producers often seek an outlet for such residues through landfill covering and other landfill-related constructions. Nevertheless, the future possibilities with such applications are rapidly decreasing, especially given the country's policy to phase out landfills (Swedish EPA, 2010a), and the waste producers are foreseeing the need for alternative outlets. Yet, the reutilisation of heterogeneous residues is still emerging, and replacing primary material with such waste-based materials is not yet a priority in the country (Eklöf, 2018). Only a few projects have been undertaken so far, where municipal bottom ash was utilised in ground construction applications (Kjellsson, 2007; Ribbing, 2007).

When it comes to the regulation of such waste reutilisation applications, Swedish Environmental Protection Agency (EPA) has developed guiding values regarding the maximum allowable content of contaminants. These guiding values are specified with respect to three application categories; construction on sensitive ground e.g. play grounds and parks, construction on less sensitive ground e.g. parking lots and noise barriers, and landfill covering (Swedish EPA, 2010b). However, the application of these guiding values varies throughout the country. In Sweden, the reutilisation of waste-classified materials in construction is considered a hazardous activity, hence, it requires permission from the respective local authorities if minimum contamination levels set by the EPA are exceeded (Sveriges Riksdag, 1998). These applications are assessed on a case-by-case basis (Swedish EPA, 2010b). A uniform criteria is however absent for such assessments, and hence, different local authorities interpret the guidelines differently (Bertils and Elvingson, 2019; Johansson, 2018). This leads to long and

uncertain authorizing processes, which often make waste producers to go for disposal options, which are more certain, and waste users to select conventional materials. The guiding values for allowable contamination levels are also based on a total hazard approach, where emphasis is put on regulating the total concentration of elements occurring in the waste. Many heterogeneous residues cannot fulfil such total concentration limits, and therefore, waste producers argue that the assessments should instead be based on a risk approach where the allowable contamination is regulated by leaching concentrations.

In contrast, several other countries in the region such as Denmark, Belgium, Finland, and Netherlands, which are socio-economically comparable to Sweden, are widely practising waste reutilisation e.g. municipal bottom ash, in ground construction applications (Dou et al., 2017; Johansson, 2018; Van Gerven et al., 2005). Unlike Sweden, these countries have developed specific and nation-wide standards that are binding, and thus not subject to varying interpretations by local authorities (Johansson, 2018). Such centralised regulations lead to more foreseeable and consistent conditions for utilisation of waste, which is beneficial both for the waste producers and users. Several of these countries also regulate the allowable contamination levels by a risk-based approach and leaching concentrations (Danish EPA, 2016; Flemish Government, 2012).

In certain countries, the governments have intervened at the actor level to facilitate the utilisation of waste by creating a market. For instance, in Denmark the authority responsible for national transportation are using bottom ash as sub-base materials in road construction (Johansson, 2018). The Dutch government has initiated the Green Deals program where government enters into partnerships with and encourages voluntary solutions by market actors to solve a waste situation (Dutch Economic Affairs Ministry, 2015). There, the government's primary role is to exert recovery demands and facilitate the removal of implementation barriers (Ellen Macarthur Foundation, 2017). Furthermore, same regulatory standards are shared between primary and secondary construction materials in the country, which creates an equal playing field for the materials in the market place. The governmental policy-, regulation-, and market-related conditions in the aforementioned countries deemed to have created more encouraging circumstances and settings for applications based on SRMs, and hence, are more conducive to the attaining of the regional resource objectives.

2.2 Significance of fines valorisation in the context of circular economy

In today's society, shredder fines can be considered important owing to several reasons. The shredding industry is, and will remain a well-established sector in the time to come, and therefore, the generation of fines will continue. Additionally, the discarded products, especially cars, are getting more and more materially complex (Andersson et al., 2019a), meaning that the high heterogeneity of fines is likely to remain or even increase. Given that the current landfill-related applications are disappearing in the long term, the shredding industry need to have secure outlets for this residue.

The valorisation of fines is of significant interest in the context of circular economy for different reasons. Circular economy represents the notion of economic development through closed material (and energy) loops where the environmental and health risk of recovery and recycling are minimised (Ellen Macarthur Foundation, 2019). For heterogeneous residues, a policy conflict between resource circulation and a non-toxic environment is unavoidable. Given the high heterogeneity of fines, a potential for increased dispersal of hazardous substances exist in relation to different recovery applications. Landfilling is plausibly a less-risky option, at least in the short term, however it comes at the cost of lost resources.

From a resource efficiency point of view, the retrieval of specific resources such as metals, plastics, and minerals are important, as it aids the returning of materials back into the production loops. The circulation of high-impact and resource-intense materials such as metals, can generate significant environmental savings due to avoided primary production (Ciacci et al., 2010). A common misconception of resource circulation is that it is always environmentally benign (Geyer et al., 2016). However, in practice, the environmental savings need to be put in relation to the resource requirements and environmental and human-health impacts of the recycling processes. From an economic point of view, the retrieval of base metals e.g. copper and zinc from fines is of significant interest to the shredding companies given their high market value. Nevertheless, the potentially low occurrence of these resources in fines and the unknown processing costs for their recovery imply a high economic uncertainty. In contrast, the bulk utilisation of fines in ground construction applications is clearly interesting for shredding companies from an economic perspective, as it can reduce the current disposal costs. Such use would also provide an outlet for all of the generated material. However, given that such utilisation only replaces primary materials such as sand, gravel, and bedrock, the environmental savings per tonne of avoiding primary production are typically much less than what could be achieved by recycling of metals for instance. Therefore, bulk utilisation might not be seen as environmentally interesting as the recovery of specific resources. However, due to the significantly larger quantities of primary materials that are replaced in such bulk utilisation, the absolute environmental impacts could still be substantial. At the end of the day, the practice of fines valorisation would come down to a trade-off between the involved economic and environmental costs and benefits.

3 Analytical approach

This chapter presents the employed systems perspective and its different levels that characterise the of the research's analytical approach. The key concepts and terms employed are framed by referring to the broader framework of the related literature.

3.1 A systems perspective for knowledge development to facilitate fines valorisation

In order to facilitate potential valorisation, it is fundamental to understand the present situation concerning fines and its management. The current practice of using fines for landfill covering is an established practice that has taken shape over time and has been arguably influenced by multiple factors related to several societal and technical aspects. The influence of multiple aspects on waste management is generally implied in previous literature on heterogeneous residues that concerns study areas such as material characteristics (Dou et al., 2017; Lam et al., 2010), marketability of secondary materials (Johansson et al., 2017, 2012), and governmental policy and regulation (Born and Veelenturf, 1997; Nayak and Apelian, 2014). Knowledge on such aspects and their influence on the current practice of managing fines is crucial to identify the challenges of facilitating fines valorisation and measures to address them.

According to Richmond (1994), systems thinking enables one to describe the occurrence of a particular situation, such as the current practice of fines management, based on an understanding of the related aspects (i.e. system components). However, a comprehensive systemic understanding should enable the explanation of a particular situation as an intrinsic result of the influence of the different components and their interrelations (Seuring, 2004; Sundberg et al., 1994). A socio-technical systems perspective is suitable for this purpose because it facilitates the contextualisation of a technically-relevant societal issue, such as fines management, in relation to a dynamic network of different institutions and actors, and various flows (e.g. material, knowledge, information, and money) within and between them (Geels, 2004; Markard et al., 2012). A major potential drawback of socio-technical systems is that the system could include too many components and their interactions could get too complicated, making it overwhelming to deal with. Therefore, system boundaries have to be drawn to exclude the aspects that are too peripheral to influence the focus of the study.

3.1.1 Employed socio-technical systems perspective

In this thesis, a socio-technical systems perspective is employed on fines management (Figure 1) in order to establish the underlying factors of the current practice of fines management. Thus, the focus is on providing knowledge to facilitate fines valorisation by identifying challenges and possible measures to address them, but not the actual development and implementation of valorisation. The current disposal-oriented practice of fines management by shredding companies is viewed as a consequence of both incentives for utilising the material in landfill covering and disincentives for developing valorisation options. Such motives (incentives and disincentives) are

understood as being influenced by external factors occurring at the institution level as well as company-internal factors occurring at the actor and material levels. The unit of analysis in the employed socio-technical systems perspective is fines management by the studied shredding company, which constitutes the actor level. Other possible operations of the shredding company that do not concern fines management are thus not studied. The focus is particularly on the shredding company because it owns the responsibility for the material and its management. Any changes to this practice, such as the development of resource recovery and recycling alternatives, would presumably have to be initiated by this actor.

Figure 1: A Socio-technical systems perspective on fines management. The thick arrows represent the internal (material and actor levels) and external (institution level) factors influencing the shredding company's incentives for fines management. The thin solid arrow represents the current utilisation of fines as landfill cover material, whereas the thin dashed arrows represent the potential valorisation of fines.

Factors that could externally influence the fines management by the shredding company occur at the institution level. Formal institutions, that is, governmental policy and regulation, is one of the two types of institutions. The EU and national waste policies provide the overarching governance to fines management. For instance, the EU waste framework directive (European Commission, 2008) defines terms such as recovery and recycling that are generally applicable to residues, whereas the end-of-life vehicles directive (ELV directive) imposes recovery and recycling targets for ELVs (European Commission, 2000) that specifically concern shredder fines. In conjunction with the regional policies, Sweden has introduced administrative legislative instruments, such as the landfill ban of organic-rich waste (Sveriges Riksdag, 2001) and landfill tax (Sveriges Riksdag, 1999). Previous fines research concerning policy and legislation (Dubois et al., 2015; Nayak and Apelian, 2014) is confined to a top-down perspective. However, as far as the actual practice of managing fines is concerned, it is important to understand how

the actors (shredding companies) interpret and react to different policy impetuses. The regulation of fines management in Sweden, similar to other residues, takes place via standards developed by the national Environmental Protection Agency (EPA), which are exercised on the municipal level. In that regard, the specificity of regulatory standards and local-authority practices in regulating waste recovery applications indicate the extent to which the potential fines recovery is facilitated in the country. Previous fines research lacks studies investigating the influence of governmental regulation on the management of the residue (Gunaratne et al., 2019). The other type of institutions is the informal institutions and consists of SRM markets, which are particularly important regarding the potential valorisation of fines, and reutilisation of fines-derived SRMs. Previous fines research concerning SRM markets is confined to the investigation of user requirements and regulatory standards on a few potential fines-derived SRMs (Allen and Fisher, 2007; Johansson et al., 2017). However, these markets are understandably more characterised by the supply, demand, and competition related to secondary as well as primary raw materials. Even though such structural aspects are important to investigate in relation to markets (Porter, 1985), what is more interesting, given the early stage of fines valorisation, is how such aspects create motives for shredding companies to process fines and produce fines-derived SRMs. Conditions in formal institutes such as specific policy instruments to induce demand for SRMs, could also influence the SRM markets.

Factors that could internally influence fines management by the shredding company occur at both actor and material levels. The actor level is addressed in relation to two types of aspects. One is the internal organisational aspects of the shredding company, which is entirely unaddressed in previous fines research (Gunaratne et al., 2019). In that regard, corporate management is addressed as it makes decisions concerning the long-term approaches to managing fines (strategic management). The strategic management of fines is understandably largely influenced by the circumstances and settings in the external environment. However, ultimately, it is company's own choice (Child, 1997), which could also be influenced by internal factors. For instance, despite favourable governmental-policy and SRM-market conditions for valorisation, the corporate management could choose to continue with the current disposal of fines and invest in something else such as improving the shredding and post-shredder resource recovery processes, other non-shredder-related operations, or completely new operations. As far as the operational management of fines is concerned, the company's capacities to influence material flows and the extent to which the company is internally organised for handling the material are considered. These aspects are understandably influenced by the strategic choice made on the corporate level on managing fines and are particularly important regarding the potential valorisation of the residue. For instance, valorising fines would require capacities such as knowledge and technological know-how, and the financial and human resources for developing those. It also requires adopting changed practices, which implies reorganisation measures such as setting priorities and defining responsibilities. Change management, in turn, implies issues related to internal communication and coordination (Rogers, 1983), given that the studied shredding company is a large organisation that has been in operation over decades, and presumably involves a scattered departmental structure (Luthans, 2011).

Apart from the organisational aspects, the actor level is also addressed in relation to internal markets for landfill construction materials (LCMs), which is the current outlet for fines. The LCM markets are considered internal and on the actor level because primarily the shredding company's own landfills, and occasionally, third-party landfills that are operationally within their control, are used for the purpose of utilising fines in landfill covering. LCM markets are particularly susceptible to governmental waste policies' fostering of landfilling.

A major drawback of employing socio-technical systems perspectives is that the significance of materiality can get subdued amidst prominent societal-level (institution and actor levels) factors (Johansson, 2013). Knowledge on materiality is most central to the handling of a heterogeneous residue, and the shredding company's knowledge on the material could largely influence their perception of fines and how they choose to deal with it. Therefore, materiality, which is internal to the shredding company, is addressed as a separate level in the employed socio-technical system. The potential valorisation of fines should be based on the knowledge of its resource potential (i.e. the potential to derive marketable SRMs), the assessment of which calls for comprehensive and in-depth knowledge on the material characteristics. There, the chemical and physical composition of the material is paramount. The occurrence of a variety of valuable resources is necessary to assess in order to identify different types of potential recovery applications so that full recovery of fines could be facilitated. Certain studies have limited the assessment to a single resource, for example, metals (Jung and Osako, 2009; Singh et al., 2016). Certain other studies have assessed the occurrence of multiple resources such as metals, minerals, and energy carriers (Allen and Kolb, 2009; Gent et al., 2015); however, material constraints such as heavy metals, corrosive substances, and inerts that could hinder recovery applications remain unassessed. Assessing the occurrence of such material constraints is necessary to identify the need for upgrading. When it comes to the development of upgrading processes, knowledge is also required on the over-time variation of the different constituents, which is an important design parameter (Allegrini et al., 2014). Yet, certain studies have characterised fines based on either one or few randomly collected samples (Morselli et al., 2010; Simona et al., 2017) that can only provide a snapshot, or representative samples (Fiore et al., 2012) that can only provide an average, of a continuous flow of the material. It is also desirable to gain knowledge on the distribution of constituents across different size fractions, based on which valorisation processes might need customisation. Yet, certain studies have restricted the composition assessment to either a single size fraction (Gonzalez-Fernandez et al., 2008; Simona et al., 2017) or a couple of size fractions with broad ranges (Fiore et al., 2012; Morselli et al., 2010). Traditionally, the resource potential assessment of primary resources would also involve technical and economic feasibility assessments of refining (Falkie and McKelvey, 1976), the process equivalent to valorising in the case of residues. Nevertheless, given the early phase of fines valorisation, an initial feasibility assessment that indicates the marketability of potential fines-derived SRMs and the upgrading requirement in delivering them are deemed sufficient.

4 Research process and method

This chapter presents the unfolding of the research and extended abstracts of the scientific articles of the thesis. Subsequently, the method used in the compilation of the thesis is presented.

4.1 The research journey

The research presented in this thesis has been conducted as part of an ongoing research project entitled Mistra Fines, which is funded by the Mistra Closing the Loop II program. The Mistra Fines project aims to contribute a framework of knowledge, methods, and necessary circumstances and settings that could facilitate the development and implementation of valorisation strategies for shredder fines. In doing so, the project inherently uses a systems perspective, which has also influenced the overall approach to the research work presented in this thesis. Following is a brief description of how the different research activities unfolded and led to the writing of scientific articles, and hence, the compilation of the thesis.

Even though shredder fines have been generating for decades, the issue of the need for its improved management has only been recently identified. Therefore, it was first necessary to understand the current knowledge levels regarding fines management. Hence, the research work started with a systematic review of globally published scientific literature that concerned the management of fines. The objective of this study was to provide guidance for systems-level research for the management of fines. This study led to the writing of the first article appended to the thesis. One of the two main findings from the literature review was that current global knowledge does not provide a coherent understanding of the materiality of fines. That is, different studies have investigated the occurrence of different constituents and involved different particle size fractions. Additionally, the variation of material composition is unknown. Consequently, the identification and development of feasible alternatives for the recovery of fines has become difficult. In addressing this issue, it was recognised that the materiality of fines is quite plant-specific, due to the differences in feed material and employed shredding and post-shredder resource recovery processes. Thus, fines generated at a particular shredding plant in Sweden was strategically sampled and characterised. There, the overall aim was to provide strategic guidance on process development for the full recovery of fines. This study led to the writing of the second article of the thesis.

The other main finding from the literature review was that previous fines research were almost entirely technically focused, involving material characterisation and process development. There, knowledge on various societal-level aspects that influence the management of fines, such as government policy and regulation and markets for secondary raw materials, are scantily addressed. The scarcity of such research leads to a significant lack of ability to explain the current disposal-oriented practice of fines management. Consequently, the identification of necessary measures to facilitate change becomes difficult. In addressing this issue, it was recognised that the

circumstances and settings that have resulted in a certain practice on fines management are quite context specific. Thus, a study on the underlying factors of the current practice of fines management in the Swedish context was carried out. In order to enable an in-depth understanding, the study involved interviews with selected employees of a specific shredding company (the same company that owns the aforementioned shredding plant) in the country. The overall aim of the study was to elicit the challenges of initiating fines valorisation by investigating the influence of policy, market, and organisational aspects on the current practices of fines management.

The findings from the three articles led to the writing of this thesis. The thesis is based on the premise that a comprehensive understanding of the present situation concerning fines and its management is necessary to facilitate potential valorisation. Hence, the following research questions were formulated. RQ1: What is the resource potential of fines generated at the studied shredding plant? RQ2: Why is the current disposal-oriented management of shredder fines sustained in Sweden? In addressing the research questions, a systems perspective that puts together the findings from the articles was employed. It recognises the relevance of various aspects at the material, actor, and institution levels, and their interrelations, in influencing the management of fines.

4.2 The appended articles

Extended abstracts of the three scientific articles that were used as the basis of this thesis are provided below, with special emphasis on the objectives and the employed data collection and analytical approaches. An overview of the articles is provided in Table 1, while the full articles are appended to the thesis.

Article I presents a systematic literature review performed to guide future research concerning the valorisation of shredder fines. In performing the review, the previous research concerning fines was systematically searched and selected. Internationally published literature during the last four decades was searched using keywords in the Scopus database. The abstracts of the resulting literature were read to screen those related to shredder fines. A maximum particle size of 20 mm was used to select the literature dealing precisely dealing with fines. The selected literature was reviewed for what has been studied, in what ways, and to what extent. Subsequently, three research topics, material characteristics, process development, and policy and regulation, were identified. The topical research was assessed regarding its scope and applicability. The scope was identified with respect to the objectives, and the breadth and depth of the studied aspects within the topic. The assessment of scope was performed by benchmarking against research on municipal bottom ash, a similar residue in terms of heterogeneity and particle size, yet with a more mature and established field of research compared to fines. The applicability was identified with respect to how specific aspects related to fines were studied within each research topic. The assessment of applicability was performed in relation to the specific situations and settings under which the generated results are valid. Thereby, knowledge gaps as well as limitations in empirical and methodological approaches in previous studies were identified and discussed.

The previous studies on fines are largely technically focused. That is, they have almost only involved material characterisation and process development for treatment and/or recovery. The material characterisation studies are largely confined to the assessment of a few out of many potentially recoverable resources and potential contaminants. Furthermore, these studies have often employed one or few randomly collected samples, which cannot show the variation of material composition. Additionally, the findings are confined to either one specific size fraction or a few fractions with large size ranges. The process development studies are often confined to the investigation of operating parameters and recovery efficiencies. Other important process attributes, such as pre-treatment requirements, output characteristics, and economic feasibility, remain largely unaddressed. Furthermore, the developed processes are mostly limited to lab-scale studies. Such isolated and narrowly-focused findings are inadequate to comprehensively establish the materiality of fines and develop upgrading and resource recovery processes. A couple of studies have performed top-down investigations on policy and regulation; nevertheless, they concern shredder residues in general. On the one hand, specific issues related to fines management remain unaddressed in these studies. On the other hand, the actor-level implications of various policy, market, and organisational aspects are yet to be investigated. In addition to the scope and applicability improvements within the topical research, a systemic understanding of their interrelations is necessary to facilitate the potential valorisation of fines.

Article II presents a study involving a systematic approach to integrated process development for the full recovery of fines. The study was performed using a mixed method consisting of quantitative and qualitative approaches. Fines generated at a specific shredding plant in Sweden was strategically sampled according to Swedish Standards and characterised with the objective of identifying potential applications for the recovery of fines based on the occurrence of potential resources and material constraints. Samples were collected twice a week to capture the weekly average. Six sub-samples, representing the primary sample (*primary fraction*) and five incremental size fractions (*sieved fractions*), were prepared and sent for analysis in an accredited laboratory in Sweden. The primary fraction was analysed to establish the average chemical and physical composition in fines as a whole, whereas the sieved fractions were analysed to establish the distribution of chemical and physical composition within the material. The intention of characterisation with respect to a range of particle sizes was that potential applications could be possibly identified with respect to different particle sizes of the material, and the subsequent development of valorisation processes could be based on that. The analysis consisted of 25 metals, and fuel properties. In order to establish the over-time variation of composition, this procedure was continued over a period of 10 weeks.

Five potential recovery applications were selected based on the established material characteristics with the objective of addressing the full recovery of fines. In order to address the retrieval of specific valuable resources, copper recovery in smelting and energy recovery in cement kilns and municipal waste incinerators were selected. Copper recovery was selected given the significant occurrence of the material in most of the analysed fractions and its high market value. Energy recovery applications were selected

given the significant heating value, especially in the larger sieved fractions. In order to address the avoided disposal of the material, bulk utilisation (to substitute primary aggregates such as sand and gravel) in ground construction and landfill covering were selected. Subsequently, the established material characteristics were benchmarked against the gate and regulatory requirements pertaining to each application, which were obtained primarily through interviews with companies involved in such applications. The benchmarking revealed the fractions with the highest recovery potential and upgrading requirement in each application. Thus, the initial feasibility of fines valorisation was assessed. The feasibility assessment was further complemented with the recoverable share of fines in each application. Thus, it was shown that the integration of various upgrading processes and recovery applications is necessary for the full recovery of fines. Confining the investigation to a single plant narrows down the generalisability of the fines' characteristics. Nevertheless, the formulated strategic approach for process development is generally applicable irrespective of the geographical location.

Article III presents a study of the underlying factors of the current practice of fines management in the Swedish context. The objective of the study was to elicit challenges of initiating fines valorisation. There, the shredding company perspective was focused since they (shredding companies) are the most central actor in the issue of fines management. The study was performed with a qualitative approach based on semi-structured, face-to-face interviews with selected employees from a specific shredding company in Sweden. Employees representing different functional areas of the company were selected in order to ensure all the operations of the company related to the generation and management of fines are addressed. The functional area *corporate management* involves overall strategic decision making. *Processing* involves the core business activity of shredding and post-shredder resource recovery, where fines is generated. *Regulatory affairs* involves issues related to waste policy and legislation, and local authorities that govern and regulate the handling of fines. *Environmental permits* works together with local authorities regarding environmental assessments as part of the authorisation of handling fines. Finally, *Sales* involves the investigation of SRM markets, and hence, the potential users of fines-derived SRMs. The interviews were transcribed and processed with tags in order to list various aspects and their relevance to fines management that were addressed. In the case of obscure or doubtful content, the author's interpretation of such content was verified with the respective respondents. Subsequently, themes that represent the implicit topics characterised by a group of tags were developed in order to identify the various policy, market, and organisational factors influencing the current practice of fines management. The factors of influence consisted of both incentives for the studied shredding company to utilise fines in landfill covering and disincentives to develop valorisation options. In this analysis, special emphasis was given to the interrelations between the different factors.

Based on the analysis of the current practice of fines management, challenges of facilitating change and initiating investments in knowledge and technology development for fines valorisation were elicited. The means to address the challenges were discussed primarily by relating to literature concerning the valorisation of other

industrial production residues, such as municipal bottom ash, shredder residues, reconstruction and demolition waste, and previously landfilled waste. Thereby, recurring issues in residue valorisation in general and specific issues concerning shredder fines valorisation in Sweden were identified. The discussion was further facilitated with empirical information obtained from the regional and national waste legislation, and the shredding company perspective of the necessary circumstances and settings for fines valorisation. The organisation-related findings of the study are specific to the involved shredding company. Nevertheless, the implications of policy and market factors are quite generalisable to the shredding industry in the Swedish context. Sweden's waste policies are largely based on the EU directives, and therefore, policy-related findings are, to a reasonable extent, deemed generalisable in the regional context as well. Due to the inherent difficulty in accurately assessing the generalisability in qualitative research, the data collection and analytical procedures are thoroughly described (Bassey, 1981; Firestone, 1993).

Table 1: Overview of the scientific articles used for the compilation of the thesis. The full papers are appended.

	Article I	Article II	Article III
Background	<ul style="list-style-type: none"> Incoherent knowledge about fines and its management deters common knowledge building. 	<ul style="list-style-type: none"> Harnessing the full recovery potential of fines has so far been overlooked. Market requirements is a significant factor in determining the resource potential. 	<ul style="list-style-type: none"> Previous fines research is almost only technically focused. Knowledge on the influence on societal-level factors is necessary to realise fines valorisation.
Aim	<ul style="list-style-type: none"> Review and assess previous studies on shredder fines in order to guide future research on its valorisation. 	<ul style="list-style-type: none"> Guide future research on integrated process development for fines valorisation in order to achieve full recovery. 	<ul style="list-style-type: none"> Contribute knowledge to facilitate change and initiate investments for knowledge and technology development for fines valorisation.
Research questions	<ul style="list-style-type: none"> Which topics of fines management have been studied, in what ways, and to what extent? How have these research approaches influenced the breadth and depth of current knowledge? 	<ul style="list-style-type: none"> How could the identification of the resource potential of shredder fines be facilitated through systematic sampling and characterisation of the material? What are the market requirements for accepting fines in different recovery applications, and what are the material constraints that need to be addressed? How to facilitate the exploitation of the full resource potential in shredder fines? 	<ul style="list-style-type: none"> What are the underlying the underlying policy, market, and organisational factors that sustain the current practice of shredder fines management in Sweden?
Method	<ul style="list-style-type: none"> Desktop search and selection of scientific articles based on pre-determined criteria. Establishing research topics, objectives, methodological approaches, and contributions. Assessment of scope and applicability of the topical findings to draw future research guidelines. 	<ul style="list-style-type: none"> Strategic sampling and material characterisation. Interviews to establish market (gate- and regulatory) requirements of the potential applications. Benchmarking material characteristics against the market requirements for initial feasibility assessment. 	<ul style="list-style-type: none"> Interviews to establish the shredding company perspective of aspects and their relation to fines management. Thematic analysis of the policy, market, and organisational factors underlying the current practice of managing fines Eliciting challenges of facilitating fines valorisation and a literature-based discussion of means to addressing them.
Findings / Results	<ul style="list-style-type: none"> Three topics: material characteristics, process development, and policy and regulation. Topical research is confined to investigating one out of many issues at a time. Research areas such as marketability of fines-derived resources and actor-level implications of policy are unaddressed. 	<ul style="list-style-type: none"> Distribution of over-time average variation of total metals, leaching metals, and fuel properties in, and across five size fractions of, fines. Different applications prefer different fractions and involved different material constraints. Valorisation targeting one single application would significantly overlook the full recovery potential. 	<ul style="list-style-type: none"> Secure outlets, legislative recognition, and low-costs create incentives to utilise fines in landfill covering. Absence of established outlets, lack of clear regulatory and market playing rules, and lack of internally organising, and capacities to influence material flows create disincentives to valorise fines.
Conclusions	<ul style="list-style-type: none"> Significant room for improvement exists concerning scope and applicability of the findings within the studied topics. Systemic approaches are required to investigate the interrelations between the research topics and other aspects influencing fines management. 	<ul style="list-style-type: none"> Fines valorisation should be initiated based on knowledge on material characteristics and market requirements. Integrated process development is necessary to harness the full recovery potential. 	<ul style="list-style-type: none"> Drastic measures on the government-policy level are necessary to challenge the current fines disposal. Established market demand, and clear regulatory and market playing rules are necessary to initiate actor investments for knowledge and technology development. Governmental intervention is key to the overall realisation of fines valorisation.

4.3 The thesis method

The overall method employed in this thesis is illustrated in Figure 2. In order to contribute knowledge to facilitate fines valorisation in the Swedish context, the current situation regarding fines and its management was portrayed by addressing the research questions. The empirical contributions of Article I influenced the design and focus of the other two articles, and provided the foundation for the socio-technical systems perspective involving the material, actor, and institutional levels. The socio-technical systems perspective was used to synthesise the findings of Articles II and III and thereby address the research questions and thesis aim. Both these articles were based on a specific case, that is, a specific shredding company (Article III) and one of its shredding plants (Article II). Such a case-based approach was employed as it enables in-depth and multifaceted knowledge development regarding a given issue and allows for the examination and interpretation of data in the context of their use (Feagin et al., 1991). The articles are used in different ways to address the research questions. Article II contributes with detailed technical findings on the materiality of fines that are necessary to assess its resource potential and facilitate the development of tailored processes for upgrading and resource recovery. In contrast, Article III employs a shredding company perspective and contributes with findings that are necessary to understand the socio-technical factors underlying the current management of fines, knowledge of which is essential to initiate changed practices. Based on the addressed research questions, challenges of facilitating fines valorisation were elicited and possible measures to address them discussed. Empirical contributions from Article I were used to provide perspectives in this discussion by relating the case-specific findings to a broader body of literature regarding fines and other similar industrial residues.

Figure 2: The overall methodological approach of the thesis.

4.3.1 Case description

The studied company operates in large scale. Annually, approximately one million tons of materials are shredded and 100 000 tonnes of fines are generated, which accounts for a significant share of the country's shredding industry. Other than post-shredder resource recovery, the company is also involved in recycling electric and electronic waste. The company was selected due to several reasons. It is a large-scale company that operates in many parts of the country and owns multiple shredding plants and landfills. Having been involved in advanced post-shredder resource recovery, it also already supplies SRMs to several markets. The large-scale operations and involvement with various local authorities and SRM markets mean that possible variations in policy and market conditions related to management of fines can be covered. Additionally, given its involvement in shredding operations for about four decades, the company was presumed to have vast knowledge and experience about the material and its handling.

4.3.2 Portraying the current picture

RQ1 refers to the knowledge on the resource potential of fines, which is fundamental to the development of any measures for the handling of the material. The resource potential was assessed in Article II using fines generated at one of the shredding plants of the case company. The assessment consisted of two main phases. The first phase involved establishing the chemical and physical material characteristics of fines (material level). There, the average composition and over-time variation of the total concentrations of 25 metals, leaching concentrations of regulated metals, and fuel properties (energy content, ash, etc.) in fines as a whole and across five size fractions were established. The motivation for the assessment of a variety of chemical and physical properties was that such comprehensive knowledge enables the identification of several potential recovery applications and their material constraints. The motivation for the assessment of the distribution of the composition and variation within several incremental size fractions of the material was that such knowledge enables the identification of desirable size fractions in relation to different recovery applications and the development of upgrading and resource recovery processes. The second phase of resource potential assessment involved assessing the initial feasibility of utilising fines in potential recovery applications. In doing so, the established material characteristics were benchmarked against the gate requirements and the regulatory requirements (institutional level) pertaining to five selected potential recovery applications. The benchmarking enabled the identification of the initial marketability, that is, the potential to meet market specifications (user requirements and regulatory standards regarding material quality), and the initial technical feasibility, or in other words, the required level of technology development for upgrading pertaining to each application. The actual valorisation of fines was not part of the research work of this thesis. Hence, neither a full assessment of the technical feasibility of the upgrading and resource recovery processes nor a full marketability assessment of the potential fines-derived SRMs was performed.

RQ2 refers to the knowledge on the underlying factors of the current disposal-oriented practice of fines management, which is fundamental in facilitating changed practices towards valorising the residue. This was primarily addressed in Article III by investigating

how different internal and external factors influence the management of fines at the studied shredding company via creating incentives for continued utilisation of the material in landfill covering and disincentives for developing valorisation options. In doing so, the shredding company perspective was focused on because they (shredding companies) are the most central actor in the issue. Internal factors were established by addressing the material and actor levels. The material level was addressed in terms of how the shredding company perceives the material complexity of fines and in what ways that influenced its management. Since Article III did not involve an in-depth study on the influence of fines' materiality on its management by the involved company, this socio-material perspective was substantiated with findings from Article II in terms of the heterogeneity and variation in material composition. The actor level was addressed in relation to the shredding company perspective on the influence of factors created by LCM markets and the internal organisational aspects of fines management. Organisational aspects were addressed both in relation to the strategic management and operational management of fines. The former consisted of the corporate management aspect of the organisation that involves strategic decision making. In contrast, the latter consisted of the aspects, namely, organisation structure, communication and coordination, and organisational capacities to influence material flows (e.g., knowledge, technology, and resources) that involve the handling of the residue. External factors were established by addressing the actor (shredding company) perspective on the influence of factors created by the institution-level aspects. Governmental policy and regulation aspects were addressed in relation to administrative and market instruments and regulatory standards and practices by local authorities concerning waste management and recovery. SRM market aspects were addressed in relation to demand and user requirements regarding the expected material quality. In addressing this research question, special emphasis was given to the interrelations between factors within and across different levels.

4.3.3 Discussing the challenges of facilitating valorisation

Based on the current picture of fines and its management, challenges of facilitating fines valorisation were elicited. There, empirical contributions of Article I were particularly used to provide perspectives. The knowledge gaps and limitations of previous research concerning fines management were used to aid the elicitation of challenges in relation to the material, actor, and institution levels, whereas the systems view on fines management was used to identify important interrelations between different factors influencing shredding company's motives for valorising the residue. Possible means to address the challenges were discussed in relation to the need to challenge the prevailing disposal-oriented practice and enabling favourable and more predictable conditions for fines valorisation. The discussion was performed primarily by relating to literature on the valorisation of similar industrial residue, for example, municipal bottom ash, shredder residues, construction and demolition waste, and previously landfilled waste. Thus, recurring issues related to the valorisation of heterogeneous residues in general, as well as specific issues pertaining to the potential valorisation of fines in Sweden in particular, were highlighted.

5 Resource potential of shredder fines

This chapter presents the findings from addressing the first research question. The resource potential is assessed in terms of the initial feasibility of fines recovery in selected applications by benchmarking the material characteristics against the respective user requirements and regulatory standards.

5.1 Copper recovery in smelting

A copper smelting plant in Sweden was involved regarding the feasibility assessment of copper recovery from fines. The highest average copper concentration in the different fractions (both the primary fraction and the size fractions ZA-ZE) was between 2 and 3 percent, significantly below the 8 percent gate requirement (Figure 3). The variation levels suggest that it could reach copper concentrations of 6 to 7 percent occasionally in size fraction ZA and ZD, but less reliably. Therefore, the enrichment of copper content is necessary prior to smelting. Receiving the material upon an additional fee (paid by the shredding company) to compensate for the low copper concentration is always an option for the smelter. Even though the gate requirements are flexible regarding the copper content, they are rigid regarding contaminants due to the potential damage certain metals can cause to the smelting process. The concentration of the most critical metals, namely, mercury (Hg), cadmium (Cd), and beryllium (Be), were generally well under the maximum limits. The occurrence of mercury concentrations in all the fractions was well below the gate limit value of 2 milligrams per kilogram (mg/kg) for all weekly samples except for one week, where the concentrations were an order of magnitude higher. Such unpredictable over-time variations make upgrading difficult and need to be avoided via upstream measures addressing waste collection and sorting.

Figure 3: Total concentrations of copper. Average and variation over 9 weeks in the primary and sieved fractions of shredder fines. The dashed line represents the gate requirement of the smelting plant.

5.2 Energy recovery in cement kilns and municipal waste incinerators

Two cement kilns and a municipal waste incineration plant in Sweden were involved regarding the initial feasibility assessment of energy recovery from fines. The gate requirements for secondary fuels in cement kilns, as well as in municipal waste

incinerators, primarily concern the heating value, ash content, moisture content, and chlorine concentration (Figure 4). As far as the cement kilns are concerned, none of the fines fractions meet the requirement of 18 megajoules per kilogram (MJ/kg) heat content. Therefore, the enrichment of organic content is required. When it comes to municipal waste incineration, the size fractions ZA-ZC fulfilled the 10-14 MJ/kg requirement. There are no such strict limit values on the ash content in either application, yet the current levels were considered too high and need to be significantly reduced, which means some separation of metals and minerals is required. Due to the high corrosivity, chlorine concentration is rather seriously regarded in both applications. The larger size fractions ZA-ZC, despite their higher energy content, need pre-treatment for chlorine reduction as the concentrations exceed the maximum tolerable values. The concentrations of the metals cadmium, thallium, mercury, arsenic, cobalt, chromium, copper, manganese, nickel, lead, antimony, vanadium in the fuel are regulated in Sweden in both applications. Generally, the average concentrations of these metals largely exceed the limit values in all the fractions of fines, and thus, metals separation is required.

Figure 4: Composition of fuel properties. Average composition and over-time (nine weeks) variation in the primary and sieved fractions of shredder fines. The dashed lines and dotted lines represent the gate requirements for cement kilns and municipal waste incinerators, respectively.

5.3 Recovery in reutilisation as bulk material

Two construction companies in Sweden were involved regarding the feasibility assessment of fines utilisation as bulk material (to substitute primary aggregates such as sand and gravel) in ground construction and landfill covering applications. Generally, these users' primary concern is the strength and stability of the material when put into use. In that regard, fines is potentially interesting for them, and there are no certain gate requirements as such. The applications are chiefly governed by the regulatory standards. Currently, such applications are handled individually by the respective local authorities based on the guiding values developed by the Swedish EPA. These guiding values primarily refer to the total and leaching concentrations of the metals cadmium, mercury, lead, copper, zinc, chromium, nickel, and arsenic. The average total metal concentrations

of all the regulated metals (Figure 5) surpass the limit values (Table 2) for all the fractions of fines. There, it is noteworthy that the high positive variations of the three critical metals recognised by the Swedish EPA (i.e. cadmium, mercury, and lead) are higher than the limit values by orders of magnitude. In contrast, the leaching concentrations of metals (Figure 5) are generally under the limit values in many of the fractions. The leaching concentrations also do not display as much of a characteristic variation across the different size fractions. Pre-treatment in the form of metals separation and stabilisation is required prior to these applications.

Table 2: Swedish regulatory standards for waste reutilisation. The guiding values on the maximum total and leaching concentrations of metals for ground construction and landfill covering are provided (Swedish EPA, 2010b, 2009).

Metals	Total concentration (mg/kg)		Leaching concentration L/S 10 (mg/kg)	
	Ground construction	Landfill covering	Ground construction	Landfill covering
Copper (Cu)	40	80	0.8	0.6
Zinc (Zn)	120	250	4	3
Lead (Pb)	20	200	0.2	0.3
Chromium (Cr)	40	80	1	0.3
Nickel (Ni)	35	70	0.4	0.6
Cadmium (Cd)	0.2	1.5	0.02	0.007
Mercury (Hg)	0.1	1.8	0.01	0.01
Arsenic (As)	10	10	0.09	0.4

Figure 5: Total and leaching concentrations (L/S 10) of Swedish regulated metals. The average and over-time (nine weeks) variation in the primary and size fractions of shredder fines. The leaching concentration of certain metals could not be shown because their concentrations were below the detectable limits of the tests.

Following the initial feasibility assessment, the overall resource potential of shredder fines is illustrated in Table 3. There is a significant need for material upgrading pertaining to the different recovery applications, due to the high occurrence of contaminants/undesirables in fines. The use of integrated processes that could simultaneously address various material constraints would be a plausible strategy to upgrade fines efficiently, both technically and economically. The integration of upgrading and resource recovery processes targeting the different size fractions (sieved fractions) preferred by the different applications would be the best way to serve this purpose. The different applications account for varying levels of the recoverable share of fines. For instance, the recovery of specific valuable resources, that is, metals and energy carriers, would lead to large quantities of fines left for disposal. Copper recovery in smelting would only recover 2 percent of fines, having 88 percent disposed of. The remaining 10 percent material corresponds to the organic fraction that would be burnt out during smelting. Similarly, energy recovery in either of the two applications would only recover about 6 percent of fines (as energy carriers) having 94 percent disposed of. However, the prior separation of the mineral content (approx. 10 percent) could directly recover that share as clinker in cement production. In contrast, bulk utilisation would recover 100 percent of the material. Yet, the opportunity to recover specific valuable resources is lost. The full recovery of fines, therefore, calls for the integration of the individual recovery applications, which is already technically facilitated in the integration of upgrading and resource recovery processes. The realisation of such integrated recovery applications would be more of a business and logistics challenge.

Table 3: Overall resource potential of shredder fines. Presented in relation to the initial feasibility of utilising fines in the selected recovery applications.

Application	Material level		Institutional level		Recoverable share of fines	Disposable share of fines
	Potential resources	Gate (user) requirements	Regulatory standards			
Copper recovery	Fractions: ZA-ZD Cu 2%-3%	Cu 8%	Not applicable	<2 % (as copper)		88 %
Energy recovery in cement kilns	Fractions: ZA-ZC 10-14 MJ/kg	18 MJ/kg Lower ash content Lower chlorine conc.	Lower total metal concentrations	6 % (as energy carriers) 10 % (as clinker)		84 %
Energy recovery in municipal waste incineration	Fractions: ZA-ZC 10-14 MJ/kg	10-14 MJ/kg Lower ash content Lower chlorine conc.	Lower total metal concentrations	6 % (as energy carriers)		94 %
Bulk utilisation in ground construction	Fractions: ZA-ZE	Not applicable	Lower total metal concentrations	100 % (as filler material)		-
Bulk utilisation in landfill covering	Fractions: ZA-ZE	Not applicable	Lower total metal concentrations	100 % (as filler material)		-

6 Factors underlying the current practice of fines management

This chapter presents the findings from addressing the second research question. The influences of the institution-, actor-, and material-level factors in creating motives for the shredding company to sustain the current practice of fines management are established.

An overview of the identified external and internal factors that influence the management of fines at the studied shredding company by creating incentives for utilisation in landfill covering as well as disincentives for valorisation is presented in Figure 6. The external factors occur at the institution level that consists of governmental policy and regulation, and SRM markets. The internal factors occur at the actor level that consists of LCM markets and organisational aspects of the shredding company, and the material level that consists of the materiality of fines. In the following subsections, the internally- and externally-created incentives for continued utilisation of fines in landfill covering are first presented, followed by the findings regarding disincentives for valorisation. These disincentives are primarily externally created, which in turn influence the internally-created disincentives. The presented findings are based on Article III unless specifically mentioned otherwise.

Figure 6: Factors underlying the current practice of fines management. Illustration of the externally- and internally-created motives due to policy, market, organisational, and materiality-related factors on the current fines management at the studied shredding company.

6.1 Incentives for utilising fines in landfill covering

One of the primary incentives for the studied company to utilise fines in landfill covering is that such use offers a secure outlet for the material due to readily accessible and internal LCM markets. In the studied company, their own landfills are primarily used for this purpose. Third-party landfills, which the company has close relationships with, are occasionally used. Decades of operations have allowed these disposal routes to gradually evolve and establish administratively and logistically. According to the personnel responsible for environmental permits, the company has continuously been striving to open up new landfills, and will most likely continue to do so, despite the government's policy to phase out landfills. Even though it was not explicitly mentioned by any of the interviewees that the company prefers to get rid of this problematic material via these available outlets, such an inclination was implicitly clear. At present, for instance, the company's knowledge about the material is confined to the assessment of a few regulated metals, which is required by local authorities as part of authorising the use of the material in landfill covering. Although several of the interviewees stress that a more in-depth understanding of the materiality is needed to facilitate valorisation, the legal representative claim that such detailed investigations of fines could also risk jeopardising the current landfill covering practice. This negative perception of the complex materiality of fines could also be substantiated by the findings of Article II, where the average total concentrations of regulated metals in fines largely exceed the Swedish EPA guiding values for reutilisation in landfill covering (see section 5.3). In addition, the high level of heterogeneity and over-time variation in the chemical and physical composition make fines a challenging material to handle in terms of continuous and standardised processes for quality assurance (see the appendix for the complete list of material characterisation results).

As far as the externally-created incentives for utilising fines in landfill covering are concerned, one of the primary factors is that such use allows the company to achieve the targets of the ELV directive. The directive requires 95% recovery of the vehicles (European Commission, 2000), and fines recovery is paramount to comply with this target since the material accounts for around 10% of the feed to the shredder. According to the involved recycling facility manager of the studied company, the plant has conducted a dedicated trial on ELVs for which the share of fines has been much less than 10%. Nevertheless, achieving the recovery target is more or less still dependent on fines recovery, and landfill covering, which is currently recognised under backfilling (European Commission Eurostat, 2011) an operation that is classified as recovery in the waste framework directive (European Commission, 2008) offers a good opportunity for doing so. The other primary externally-created incentive for utilising fines in landfill covering is that such utilisation of waste is tax-exempt in Sweden due to the recovery classification (Statens Ofentliga Utredningar, 2005), thus, making the operational costs of handling fines much lower than those of landfilling, which is the currently available alternative for the material. The current costs of landfill covering range from 100 to 300 SEK/ton for the company, and given today's landfill tax of 500 SEK/ton (Sveriges Riksdag, 1999), the operational costs would be significantly higher if fines were landfilled.

6.2 Disincentives for valorising fines

According to several of the interviewees, the studied company has previously undertaken several initiatives for fines valorisation targeting ground construction applications. However, all of them turned out to be unsuccessful due to multiple factors. Such factors create disincentives for investing in fines valorisation, and primarily occur in the external environment. One of the most prominent externally-created disincentives for valorising fines is the lack of clear regulatory standards that makes the shredding companies uncertain regarding the realisation of potential valorisation applications (i.e. valorisation-based recovery applications). At present, the only available regulatory standards in the country are the EPA guiding values on the allowable contamination levels in SRMs to be used in ground construction applications (Swedish EPA, 2010b). These centrally-developed values could not accurately address the varying material-, application-, and site-specific conditions of individual applications. Additionally, such applications are regulated on a case-by-case basis by local authorities that often lack experience, resources, and qualified personnel (Bertils and Elvingson, 2019) perform accurate risk assessments. According to the interviewed legal representative of the studied company, they have previously experienced large inconsistencies in how these guiding values for allowable contamination levels are applied for fines reutilisation in ground construction in different situations. Such inconsistency is further evident in that the Swedish Transport Administration, which is the largest potential user of fines-derived SRMs in ground construction, has been unaware of the applicable conditions for such use (Johansson, 2018).

Another regulation-related disincentive for valorising fines is that the regulatory practices have created unfavourable circumstances for waste recovery applications, thus rendering the realisation of fines valorisation almost impossible to accomplish for shredding companies. For instance, the EPA guiding values presume the bare use of SRMs in ground constructions (Avfall Sverige, 2017), which is an unlikely practice as the materials and their contaminants will be either bound to or contained within natural materials, thus partly immobilised. Additionally, the guiding values are primarily based on the total concentration of metals (Swedish EPA, 2009) despite that the actual environmental and health impact is caused by their biological availability (Singh and Lee, 2015), of which leaching concentrations are a stronger indicator (Blasenbauer et al., 2020). Furthermore, the current authorising processes by local authorities emphasise local impacts and pollution risks of waste reutilisation, whereas the global or regional benefits in terms of avoided impacts from primary production remain somewhat neglected. Such a risk-prudent regulation could, to a large extent, be explained by the strong emphasis put in the waste framework directive on minimising hazards of waste handling (European Commission, 2008). However, it generates a lack of trust at the studied shredding company, which foresees that any attempt to valorise fines will not undergo a fair trial in the authorising processes.

Continuing on the externally-created disincentives, the market conditions for SRMs in Sweden render fines valorisation a high investment risk for shredding companies. SRM markets in Sweden are generally characterised by low user willingness (Johansson,

2018), which implies that the demand for fines-derived SRMs is low and the potential users rare. The abundance of primary materials at competitive prices, and potential users having adapted their technical processes, knowledge, and regulatory understanding for such materials, could be seen as the primary reason for the low demand for SRMs. Additionally, authorisation processes involve quality assurance for each and every occasion SRMs are reutilised, which is an arduous, time-consuming process for shredding companies, and makes them unable to maintain timely deliveries. These quality assurance requirements are partly due to the lack of specific regulatory standards to govern such applications. When it comes to competition between alternative SRMs, the potential demand for fines-derived SRMs is further reduced given the availability of more homogeneous and less-contaminated alternatives such as iron sand, slag, and construction and demolition residues in the country. Hence the company believes the economic prospects of fines valorisation to be extremely low. Furthermore, the lack of demand makes price setting for potential fines-derived SRMs unpredictable, making the economic assessment of different valorisation options difficult. There is also a significant lack of market specifications regarding the expected SRM quality, which is key to develop technical processes for material upgrading and resource recovery. One part of the market specifications is the user requirements concerning material quality, the lack of which is related to the aforementioned lack of demand for SRMs. The potential users of fines-derived SRMs have not had the need for such materials. The other part of market specifications is the regulatory standards for SRM applications, the lack of which is also presented earlier in this section. According to all the involved process managers of the company, despite the availability of a certain level of technology and know-how at their disposal, they are unable to process fines due to the absence of such market specifications.

A major internally-created disincentive for valorising fines is the lack of focus on the material on the corporate management level of the company. This situation is primarily due to the circumstances and settings in the external environment that foster fines disposal and are uncondusive to fines valorisation. According to the manager of the alternative raw materials unit, the company would rather continue with the current disposal-oriented approach for fines until it is no longer an option. As stated by the interviewed processes managers, there are also existing issues and potential for improvement in the company's mainstream processes involving the larger fractions of shredder residues that carry higher resource yields and economic prospects. Hence, corporate management has so far prioritised investments in improvement measures to these mainstream processes. Plausibly explained by the lack of focus on the strategic management of fines at the corporate level, the operational management of the material is somewhat in limbo, which creates further disincentives for developing valorisation options. One such disincentive is the lack of internally organising for the handling of the material. Currently, the responsibility of handling fines is not formally recognised in the company's organisation structure, and consequently, a substantial lack of communication and coordination exists between the different functional units of relevance for the management of the residue. Thus, scattered and isolated initiatives (within the individual functional units, e.g. *processing, research and development, and sales*) have been undertaken for valorising fines, none of which have led to successful

implementation (mentioned in the beginning of Sub-section 6.2). Such failure of implementing fines valorisation options could also be attributed to the lack of a structured and co-ordinated approach in handling the material, which is necessary to overcome various implementation barriers (Lozano, 2009) due to the presumably high embeddedness in aspects such as routines and protocols of obtaining environmental permits, generating contractual agreements with landfill owners, and logistical arrangements, having sustained over decades of utilising fines in landfill covering. The other main disincentive for valorising fines at the operational level is the limited capacities for improved handling of the material. As mentioned previously, the current knowledge on the materiality of fines is primarily confined to the occurrence of a few regulated substances. According to the involved process managers of the company, knowledge and technology development towards fines recovery have been deprived of necessary financial and human resources, which are channelled to the prioritised mainstream processes. Consequently, the company's knowledge on the potentially recoverable resources and material constraints in fines is limited, making the development of tailored technical processes for upgrading and resource recovery largely difficult.

7 Challenges of facilitating fines valorisation

This chapter presents a synthesis of the challenges of facilitating fines valorisation in Sweden, elicited from the findings from the research questions, followed by a discussion on the possible means of addressing them.

The decreasing demand for LCM and the ongoing phasing-out of landfilling has triggered the studied shredding company to foresee that future fines management has to settle outside of landfills. However, the current factors underlying fines management do not yet imply strong enough incentives for them to deviate from fines disposal and opt for valorisation. From their perspective, the current practice of utilising fines in landfill covering offers a somewhat safe outlet, at least in the short term. It is a legislatively compliant and low-cost disposal option for this problematic material. On the other hand, the lack of specific and consistently-applied regulatory standards for waste reutilisation, environmentally-prudent regulatory practices of local authorities, and an absence of well-developed SRM markets make investments in fines valorisation regulatory-wise uncertain and economic-wise risky. Largely influenced by these external factors, the strategic management of fines is deprioritised in corporate level, and consequently, the operational management of the material is compromised. The handling of fines in the studied company is somewhat informal and unorganised, and the knowledge and resources for its improved handling are somewhat lacking. For instance, the limited knowledge about the materiality makes it difficult to assess the resource potential of fines, which is required to enable the development of standardised processes for upgrading and resource recovery. However, such knowledge has now been provided in this thesis (Section 5), and it shows that fines valorisation is technically challenging and would require significant investments in knowledge and technology development. At present, however, such investments and changed practices for managing fines do not seem justifiable for the company. In order to increase their motives for opting for fines valorisation and initiate investments in knowledge and technology development, two-folded measures on the institution level are primarily needed. That is, conditions that challenge the current disposal-oriented practice of fines management need to be set, and favourable and more predictable conditions for fines valorisation need to be enabled.

7.1 Challenging the current disposal-oriented practice

Initiating changed practices can only be expected through conditions challenging the circumstances and settings that sustain the current disposal-oriented practice of managing fines. Thereby, shredding companies could be compelled to seek valorisation-based alternatives. An indirect, yet a practical means for realising that would be the declassification of landfill covering as backfilling. It would strip landfill covering from its current recovery status, thus necessitating opting for alternative recovery strategies for fines in order to fulfil the ELV directive targets. The measure has been advocated as necessary to initiate waste recovery strategies in general (Arm et al., 2017), and its implementation is likely given the increasing focus towards the value-added recovery of industrial residues on the EU level (European Commission, 2011). This measure would

also strengthen the ELV directive's requirements for only thermal recovery other than recycling, thus prompting shredding companies to ponder valorisation strategies for fines instead of disposal-oriented ones. Even though fines generated from ELVs is much less according to the studied company, it could vary significantly industry-wide, given the differences in shredding and post-shredder resource recovery processes. Hence, such a revision of backfilling would still impose a significant impact on how fines is managed. Taking away the recovery classification would also remove the existing landfill tax concessions currently cherished by landfill covering in Sweden. That would render fines disposal significantly more expensive, thus making it economically worthwhile to consider other recovery strategies. An alternative, or even complementary, means to indirectly challenge the current conditions for fines management would be to expedite the country's policy decision to phase out the existing landfills, despite the already decreasing demand for landfill cover materials. The studied shredding company has so far managed to open up new landfills and get exemptions for the landfilling of fines. This would likely continue into the future unless phasing out landfills is expedited. A direct and more drastic means to challenge the current practice of managing fines would be to impose bans or significantly higher taxes on fines disposal and simultaneously mandate resource recovery. An example of such a regulatory strategy can be taken from the Netherlands, where the landfilling of potentially recoverable waste is banned (Lieten, 2018). Municipal bottom ash is one such material for which valorisation applications have been consequently developed (Kahle et al., 2015). However, the success of those applications has not been just due to the landfill ban but also the availability of well-established markets for SRMs. In contrast, a disposal ban on fines in Sweden would be an isolated one, as the fines-derived SRMs would most likely not be equally well received by end users, and thus might only penalise shredding companies.

7.2 Enabling favourable conditions for valorisation

Challenging fines disposal alone would not suffice to realise fines valorisation. It is equally important to establish favourable and more predictable policy- and market-related circumstances and settings to motivate investments and ensure its successful implementation and long-term sustenance.

7.2.1 Outlets for fines-derived SRMs

In order for shredding companies to feel confident in venturing into fines valorisation, the potential fines-derived SRMs need to have secure outlets. Otherwise, they might instead choose to take shortcuts for recovering without any effective valorisation, such as mixing fines with primary raw materials to enable bulk utilisation in ground construction applications. The availability of an adequate and predictable demand for SRMs, therefore, is crucial. Currently, the utilisation of SRMs in Sweden is in an early phase and characterised by low user acceptance, and hence, governmental intervention could play a central role in creating market demand for such materials. An important means to accomplish this would be the use of state-owned users. Examples of such cases can be taken from Denmark and the Netherlands, where governmental authorities responsible for transportation utilise bottom ash-derived materials in the construction

of roads and pavements (Johansson, 2018). The same could be implemented in Sweden involving the national transport administration (Trafikverket), given the similar socio-economic context. Green criteria in public procurement and tenders in relation to large infrastructure projects in general is another possible and somewhat complementary measure to enhance the demand for SRMs. Currently, most of the foreseeable areas of SRM utilisation exist in relation to ground construction. Possible future developments might extend such bulk applications to more advanced utilisation of residues in, for example, structural construction, or even as raw material in different production and manufacturing industries. As much as governmental interventions, shredding companies also need to actively seek possible SRM markets. In that regard, stricter enforcement of the ELV directive could be an important way forward. Following up on the actual fulfilment of the directive targets and requiring more transparency in how they were reached could create more pressure on shredding companies to find avenues for valorising fines. Yet, the fact that SRM logistics are not properly developed and costs are high (Andersson, 2018) could pose a challenge for fines valorisation initiatives by shredding companies. Governmental interventions, such as state-mediated procurement organisations that could act as hubs to collect and store various types of SRMs and distribute to different users, are plausible strategies to address that.

As much as having outlets for fines-derived SRMs, the economic consequences of producing them are of great interest for shredding companies as profit-oriented organisations. For instance, the studied company makes investment decisions more or less solely based on their economic potential. Likewise, a UK-based shredding company has, for instance, chosen to invest in thermal treatment rather than meeting the ELV directive targets, based on the economic prospects of the former (Khodier et al., 2018). The economic prospects of fines valorisation are presumably quite low, especially given the limited resource potential and the significant material constraints that need to be resolved by costly upgrading processes. Therefore, in order to justify such investments in fines valorisation, policy measures such as excessive taxing of fines disposal could be inferred as the avoided costs of disposal would then become substantial. Given that the possible valorisation of fines is new, exogenous (policy) support is also needed via market instruments such as tradeable credits based on amounts recycled, pre-charged disposal taxes that shall be refunded upon the recycling of residues, taxed primary resources (Dubois et al., 2015; Tekie, 2017), and even investment support, which could make fines valorisation anchor as an industrial activity, and fines-derived SRMs be competitive in the marketplace.

7.2.2 Clear market and regulatory playing rules

In order for the shredding companies to be able to cater to the available outlets, fines valorisation needs to be governed by clear market and regulatory playing rules. As far as market playing rules are concerned, the price setting of fines-derived SRMs is essential. The evolving of predictable pricing mechanisms for fines-derived SRMs relies on an established supply and demand, which could be facilitated via the creation of outlets for such materials, and making them competitive in the marketplace (discussed in the previous section). Another major aspect of market playing rules is the existence

of user requirements on expected material quality, the lack of which is a primary reason why residues seldom find it hard to return to production loops (Shahbazi et al., 2013). An established market demand is also expected to lead to the development of such material specifications by potential users, thus enabling the shredding companies, as the suppliers, to identify and develop tailored technical processes for upgrading and resource recovery. The ability to set prices for potential fines-derived SRMs and identify technical processes to produce them enables accurate economic assessments of fines valorisation, thus reducing the investment risks. Facilitating the reutilisation of fines within the legislative framework is an important means for both enhancing the market acceptance of fines-derived SRMs and having clear user requirements available. However, the end-of-waste criteria (European Commission, 2008), which is necessary to bring such material back into industrial loops, is not being practiced for any waste in Sweden (Bertils and Elvingsson, 2019), let alone shredder fines. Additionally, the recognition of fines in regulations such as REACH (European Commission, 2006), which governs the use of materials in production and manufacturing, would require meticulous investigation on the potential health risks associated with the material. Given the early phase of SRM utilisation in the country, and the slow pace of bureaucratic administrative processes in that regard (Johansson, 2018), the implementation of such legislative measures is apparently far-fetched.

As far as regulatory playing rules of fines valorisation are concerned, arguably, the most important aspect is the availability of specific regulatory standards for the allowable contamination levels in the waste to be used. Similar to user requirements, such specific standards enable shredding companies to identify and develop technical processes for upgrading and resource recovery. It also reduces the current uncertainties related to authorising processes. In contrast to the Swedish guiding values for allowable contamination levels in waste to be utilised in ground construction, several EU countries have developed specific standards, which are nation-wide applicable and binding. These standards are also often more conducive to the use of SRMs, where, for instance in Belgium, the allowable total concentration limits in the waste are many times higher, while the leaching concentration limits are stricter than in Sweden (Johansson et al., 2017). In order to minimize pollution concerns, such limit values in these countries are often combined with different safety measures and requirements, such as maximum allowed quantity and layer-thickness of residues in Denmark and the Netherlands, and minimum distance and elevation from water sources in Belgium (Dou et al., 2017; Van Gerven et al., 2005). Urgent recognition of the possibility of a rapid increase in the demand for SRMs and the consequent drafting of legislation by governmental institutes are necessary to realise such regulatory standards. Policy initiatives, such as classifying wastes/residues as anthropogenic stocks, which is currently under discussion concerning landfills (UNECE, 2018), can drastically enable the development of such legislation. Nevertheless, in contrast to the aforementioned countries, the recognition of the need for increased use of SRMs is so far limited in Sweden, plausibly owing to the abundance of primary resources and landfill space.

8 Thesis contributions

This chapter presents the significance of this thesis's contributions in facilitating the valorisation of fines in particular as well as heterogeneous residues in general, followed by a general reflection on the circular economy concept.

A significant opportunity for the valorisation of heterogeneous industrial residues seems to exist in our societies considering their material compositions and the large amounts in which they are generated and disposed of. Nevertheless, the research and development are still in their infancy concerning many of such residues, and very few initiatives have taken place. The valorisation of a given residue is only realisable given the availability of systemic knowledge on the current situation concerning the material and its management. However, previous fines research is scattered in isolated research topics (Gunaratne et al., 2019), and lacks systemic knowledge in relation to multiple technical, organisational, market, and policy aspects concerning the management of the residue, thus making the development and implementation of valorisation strategies difficult. This thesis portrays the current picture of fines and its management in the context of Sweden by using a socio-technical systems perspective, where the resource potential of fines and the underlying factors of the current practice of its management were investigated on the material, actor, and institution levels. The investigation of the former facilitates the development of upgrading and resource recovery processes, whereas the latter is necessary to identify the challenges of initiating actor investments in knowledge and technology developments for doing so, and possible measures to address them.

Assessment of the resource potential of a given residue should comprehensively reveal the occurrence of potentially recoverable resources as well as possible material constraints. However, previous fines research is often confined to the assessment of a few targeted valuable materials, for example, base metals (Gunaratne et al., 2019). In this thesis, fines has been characterised in terms of the occurrence of a broad range of chemical and physical properties in order to enable the identification of multiple potential recovery applications and possible material constraints. Unlike previous fines research that has only analysed a few random or representative samples (Gunaratne et al., 2019), strategic and systematic sampling has been performed to establish the average and over-time variation levels of the material composition in order to provide essential process design information (Allegrini et al., 2014) for upgrading and resource recovery. Additionally, in contrast to previous fines research that has analysed either a single size fraction or few broad-range size fractions (Gunaratne et al., 2019), the distribution of the material composition across several incremental size fractions of fines is assessed in order to enable process development targeting specific particle sizes. In addition to the material characteristics, the resource potential assessment should also reveal the marketability of a given residue, which is barely addressed in previous fines research (Gunaratne et al., 2019). This thesis benchmarks the established material characteristics against the market specifications (i.e. user requirements and regulatory standards) and stipulates the need for material upgrading pertaining to selected potential recovery

applications. The assessed resource potential is unique to fines generated at the studied plant given that material characteristics are highly plant specific, and the market specifications are unique to the Swedish context. Nevertheless, the developed strategic and systematic methodological approach for comprehensively assessing the resource potential, already in an early phase to facilitate tailored upgrading and resource recovery processes, is applicable, not only for fines but also for other heterogeneous residues, and in any industrial context. As far as process development for fines valorisation is concerned, previous fines research has been largely confined to one specific application (Gunaratne et al., 2019), which neglects the need for full recovery of the residue. This thesis showcases, based on the assessed resource potential, an integrated process development approach to address multiple material constraints and harness multiple recovery opportunities so that full recovery of fines is achieved. The approach is generally applicable independent of the type of heterogeneous residue (fines or other) or the geographical context.

When it comes to investments in knowledge and technology development for the valorisation of a residue, particularly one such as fines that is disposed of, it is fundamental to understand the factors that influence actors' motives concerning its management. Even though such factors could occur in different socio-technical levels, previous fines research is largely limited to the investigation of a couple of top-down governmental-policy studies involving administrative and market instruments governing the handling of shredder residues in general (Gunaratne et al., 2019). As much as such studies do not address specific issues related to fines management, they fail to address how the involved actors interpret and react to different policy stimuli, which is paramount in putting policy into practice. This thesis creates in-depth insights from a shredding company perspective (as the most central actor in fines management) on the external and company-internal factors that sustain the current disposal-oriented management of fines. Thus, not only the bottom-up perspective on governmental policy and regulation but also how the shredding company perceives the SRM -markets and the complex materiality, in relation to the management of fines are shed light upon. The external factors (i.e. related to governmental policy and regulation, and SRM-market aspects) explicitly refer to the Swedish context, yet are applicable to fines and other heterogeneous residues in the country in general. In contrast, the internal factors (i.e. related to LCM markets, materiality, and organisational aspects) are highly case-specific, and therefore, are confined to, at the least, fines management by the studied company, and at the most, the shredding industry in Sweden. Some of the identified challenges of initiating fines valorisation, such as creating regulatory playing rules, are commonly found with other similar heterogeneous residues, whereas improving the competitiveness in the marketplace is a rather specific challenge for fines-derived SRMs given the early phase of fines valorisation and the relatively low resource potential of the material.

The empirical and methodological contributions of this thesis show what sort of knowledge is required and how such knowledge is acquired so that the valorisation of heterogeneous residues could be initiated, and materials could be returned back to use in society. A central problem this investigation emphasises, in relation to the ongoing

regional and national initiatives towards a circular economy, is the overall challenge of balancing resource circulation with environmental and human-health risks of possible contamination in residue valorisation. In spite of that, a problem also exists in how the circular economy is conceptualised today in Sweden: it is more focused on the economic development via business opportunities based on circular strategies than addressing the resource conservation dimension of sustainability. A clear discursive transformation in approaching circularity in the country is visible where the problematisation of material and energy flows has shifted from both inflows and outflows, to only outflows during the last two decades (Johansson and Henriksson, 2020). This latter orientation is also reflected in the EU action plan for circular economy (European Commission, 2020), and would only complement the traditional consumption-based economic development. In order to realise circular economy sustainably, a balance between economic development and resource conservation is necessary. Resource scarcity is already an increasingly pressing problem in economic development, and it is only a matter of time before resource conservation becomes inherent in the circular economy.

9 Conclusions

This chapter presents the major takeaway points concerning the current situation regarding fines and its management and the challenges of facilitating fines valorisation in the Swedish context.

In the present context in Sweden, shredding companies are doing what seems rational, by undertaking a disposal-oriented approach to managing fines. The current practice of utilising fines in landfill covering offers a secure outlet for the material. It is an established practice, and there is still a significant demand for landfill cover materials. Additionally, it provides fines management with a low-cost disposal option, which is facilitated within the existing legislative framework. On the other hand, the complex materiality, lack of marketability of SRMs, and unfavourable governmental regulation of waste recovery create strategic disincentives for shredding companies to opt for valorising fines.

The realisation of valorisation strategies needs to be based on a comprehensive understanding of the resource potential and initiated and sustained via institutional conditions and responsive actors, in conducive to driving fines away from disposal and towards investments in knowledge and technology development for upgrading and resource recovery. The studied material shows that fines generally could carry a significant resource potential, and hence, valorisation prospects. The full recovery of the material requires integrated processes that could simultaneously address various material constraints and harness multiple resource opportunities.

Nevertheless, in facilitating fines valorisation, drastic policy measures that challenge the disposal-oriented options for the material and demand resource recovery are necessary. Favourable circumstances and settings on the institution level are also needed to justify investments in knowledge and technology development for valorisation. Policy-driven SRM markets are necessary to ensure that outlets exist for fines-derived SRMs, and favourable market instruments are necessary to ensure such materials remain competitive in the marketplace. Shredding companies as potential investors of fines valorisation also need to feel confident about such applications. In that regard, the setting up of regulatory and market playing rules is key. The availability of clear regulatory standards and user requirements, and more favourable regulatory practices that are congruent with the ambitious regional resource policies, would build trust in shredding companies regarding the realisation of valorisation applications. The availability of predictable pricing mechanisms for fines-derived SRMs would enable accurate economic assessments of valorisation applications and reduce the investment risk for shredding companies.

Governmental interventions are paramount concerning both challenging the current practice of fines management and enabling favourable and more predictable conditions for fines valorisation. The state could play a central role by not only facilitating actor-initiated solutions via the removal of implementation barriers but also taking part in them via public-private partnerships. Such approaches shall also emphasise the

significance of shredding companies, as the responsible actor in the issue, taking voluntary initiatives for fines valorisation. It is worth noticing that waste policies are more likely to target relatively higher-value or larger-volume residues, whereas fines valorisation would rather have to be facilitated within this wider policy framework. Anyhow, the realisation of intricate government-driven waste valorisation initiatives in Sweden, would require state-level recognition and fostering of SRMs as a new demand paradigm.

The research work presented in this thesis showcases a generally applicable strategic methodological approach to assess the resource potential of fines, and thereby, facilitate integrated process development for the full recovery of the material. It also elicits the systemic challenges that need to be addressed in order to enable actor investments for knowledge and technology development for the valorisation of this *waste-of-waste* in the Swedish context.

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Appendix

Detailed material characteristics of fines

	Primary fraction	ZA (7.10-5.00 mm)	ZB (5.00-3.35 mm)	ZC (3.35-2.00 mm)	ZD (2.00-0.25 mm)	ZE (0.25-0.063 mm)
Total metals (mg/kg)						
Al	20 800	56 400	37 800	27 800	26 000	17 500
Ba	3 260	3 460	4 740	4 260	3 280	2 600
Be	0.65	0.64	0.67	0.66	0.64	0.57
Pb	1 660	1 170	1 300	1 170	1 488	2 300
Fe	226 000	106 400	100 800	114 000	286 000	220 000
Cd	22	9	11	28	21	51
Ca	39 200	34 200	42 200	44 000	33 600	40 000
K	1 980	1 240	1 600	1 660	1 600	2 600
Co	68	127	46	30	70	92
Cu	13 440	30 740	20 040	18 300	20 720	4 525
Cr	1 426	1 154	940	592	2 260	1 160
Hg	5.43	1.08	1.95	2.67	4.90	1.11
Mg	6 260	4 220	4 920	5 020	4 440	9 900
Mn	2 320	1 028	1 320	1 326	2 800	2 650
Mo	83	119	69	65	152	110
Na	3 720	1 980	2 700	2 780	2 740	5 275
Ni	1 166	606	698	422	1 234	1 020
Sn	358	760	444	392	298	270
Ti	1 480	758	1 006	990	1 140	2 100
V	56	50	49	46	61	63
Zn	30 200	13 500	12 880	18 200	37 800	27 750
Sb	158	398	284	268	156	153
As	48	18	19	25	29	38
B	384	278	280	272	300	603
Si	106 400	78 200	94 200	95 800	108 000	122 500
Leaching metals (mg/kg)						
As	0.2	0.2	0.2	0.2	0.2	0.2
Ba	< 5.00	< 5.00	< 5.00	< 5.00	< 5.00	< 5.00
Cd	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03
Cr	< 0.20	< 0.20	< 0.20	< 0.20	< 0.20	< 0.20
Cu	0.34	0.30	0.35	0.45	0.30	0.30
Hg	0.006	0.005	0.005	0.005	0.005	0.005
Mo	0.68	0.20	0.25	0.35	0.60	0.95
Ni	0.28	0.10	0.15	0.10	0.15	0.15
Pb	0.14	0.10	0.10	0.15	0.30	0.15
Sb	0.18	0.06	0.06	0.08	0.25	0.25
Zn	1.40	0.55	0.55	2.60	2.75	0.60
Energy properties						
Heat (MJ/kg)	5.49	14.02	12.08	10.28	4.05	3.59
Ash (% d.b.)	82.38	60.86	62.10	65.32	88.94	87.08
Moisture (% w.b.)	14.87	14.44	15.49	14.88	14.58	14.85
Cl (% d.b.)	0.28	1.20	0.97	0.70	0.20	0.23
S (% d.b.)	0.46	0.30	0.38	0.42	0.39	0.49

Appended Articles

Articles

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FACULTY OF SCIENCE AND ENGINEERING

Linköping Studies in Science and Technology, Licentiate Thesis No. 1864, 2020
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